

# Reentrant temperature dependence of critical current in superconductor - ferromagnet - superconductor junctions based on PdFe alloys.

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The magnetic and transport properties of  $Pd_{0.99}Fe_{0.01}$  thin films have been studied. We have found that the Curie temperature of the films is about 20 K and the magnetic properties strongly depend on temperature below  $T_{Curie}$ . We have also fabricated the set of superconductor-ferromagnet-superconductor josephson junctions  $Nb - PdFe - Nb$ . The temperature dependence of the junctions with the ferromagnet layer thickness of about 36 nm shows the reentrant behaviour that is the evidence of the transition of the junction into the  $\pi$ -state.

The proximity effect in superconductor-ferromagnet heterostructures attracts a great interest of several recent decades. As it was shown earlier ([1, 2] and [3] as a review) the decay of the superconducting order parameter in the ferromagnet is accompanied by the sign-changing oscillations. The unambiguous evidence of sign-reversal spatial oscillations of the superconducting order parameter in a ferromagnet was provided by the observation of the  $\pi$ -state in *SFS* Josephson junctions [4, 5, 6, 7]. 'π-junctions' [8] are weakly coupled superconducting structures with the ground state phase difference of the macroscopic superconducting wavefunction  $\varphi = \pi$ . They are characterized by the anomalous current-phase relation  $I_s = I_c \sin(\varphi + \pi) = -I_c \sin \varphi$  with negative critical current [8]. Spatial oscillations of the superconducting order parameter in a ferromagnet close to an *SF*-interface were predicted in Ref. [2]. The physical origin of the oscillations is the exchange splitting of spin-up and spin-down electron subbands in ferromagnets. The period is  $\lambda_{ex} = 2\pi\xi_{F2}$ , where the oscillation (or "imaginary") length  $\xi_{F2}$  can be extracted from the complex coherence length  $\xi_F$  in a ferromagnet:  $\frac{1}{\xi_F} = \frac{1}{\xi_{F1}} + i\frac{1}{\xi_{F2}}$ . In the case of large exchange energy and negligible magnetic scattering in the *F*-layer the imaginary length  $\xi_{F2}$  and the order parameter decay length  $\xi_{F1}$  are equal [2]:  $\xi_{F1} = \xi_{F2} = \sqrt{\hbar D/E_{ex}}$ , where  $D$  is the diffusion coefficient for electrons in a ferromagnet and  $E_{ex}$  is the exchange energy responsible for sign-reversal superconductivity in a ferromagnet. The transition into the  $\pi$ -state manifests itself as a reentrant behaviour of critical current density as a function of *F*-layer thickness.

The most promising way to observe the transition to the  $\pi$ -state is to use weak ferromagnetic alloys as an interlayer. Weak exchange interactions in such alloys lead to large values of characteristic lengths: the oscillations period  $\lambda_{ex}$  and the decay length  $\xi_{F1}$ . This gives an opportunity to obtain a detailed  $j_c(d_F)$  curve and to demonstrate its reentrant behaviour (see [9] for CuNi alloys and [5] for PdNi alloys). Additionally weak ferromagnetism in alloys allows to drive 0- $\pi$  transition point by temperature ([4], [9]). This causes the reentrant temperature dependence of SFS junctions critical current density that is the unambiguous proof of the 0 -  $\pi$  transition.

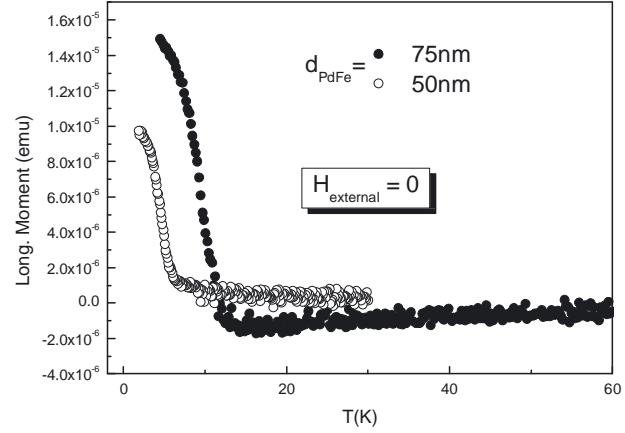


FIG. 1: The magnetic moment vs temperature dependance of thin film  $Pd_{0.99}Fe_{0.01}$  in zero external magnetic field obtained by means of SQUID-magnetometry.

This effect was observed for a first time in Ref. [4] in  $Nb - Cu_{0.48}Ni_{0.52} - Nb$  SFS-junctions and later the reentrant  $I_c(T)$  dependence was observed in SFS-junctions based on others  $Cu_{1-x}Ni_x$  alloys ([6], [9], [10]).

It is well known that alloys  $Cu_{1-x}Ni_x$  possess the ferromagnetic properties only at sufficiently large concentrations  $x > 0.44$ . The large amount of ferromagnetic impurities is able to modify strongly the transport properties of initial materials and to complicate an analysis of an experimental data. One can avoid this difficulties if using the alloys with very small concentration of ferromagnetic atoms ( $x \leq 0.01$ ). For realization of this approach it is very useful to use Pd or Pt as a starting nonmagnetic material. According to stoner criteria this materials are very close to ferromagnetic ordering and insertion of very small amount of magnetic atoms is to lead to strong polarization of electrons. If the amount is large enough and the polarized regions overlap then the alloy will possess ferromagnetic properties. The ferromagnetic properties of alloys  $Pd_{1-x}Fe_x$  were studied in Refs. [11]-[24].

In this article we have studied the magnetic and transport properties of thin films  $Pd_{1-x}Fe_x$  obtained by rf-

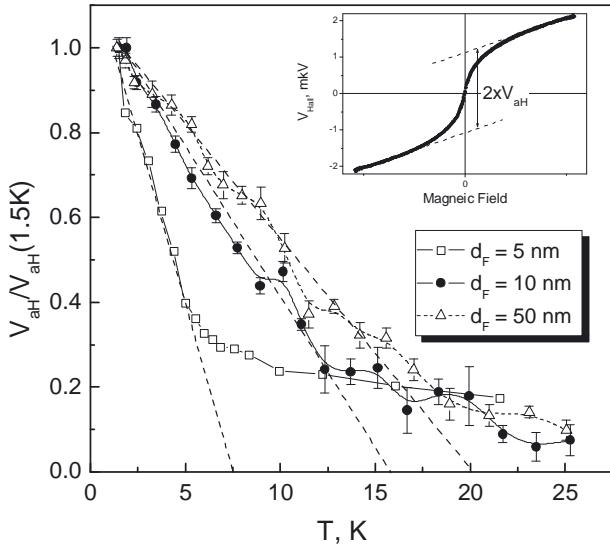


FIG. 2: The normalized Hall voltage vs temperature dependence of thin film  $Pd_{0.99}Fe_{0.01}$ . Dashed lines show an extrapolation of this curves to zero voltages in order to estimate the Curie temperature. The inset shows the typical Hall voltage vs the magnetic field dependance and the definition of  $V_{aH}$  value.

sputtering in argon atmosphere. The concentration of Fe in target was about 1%. The geometry of samples was formed by means of rf-ion etching in argon plasma. The resistivity of films in thickness range from 5 to 50 nm was about  $40 \mu\Omega \cdot cm$  and very slightly differed with thickness and temperature. The magnetic properties of PdFe films were studied by means of SQUID-magnetometry and the anomalous Hall effect measurements. We found that spontaneous magnetic moment arises at temperatures below  $10 \div 12 K$  if the film thickness is greater than 50 nm (see fig. 1). We did not find any magnetic response studying the thinner films. Hall measurements showed that the ferromagnetic properties of the films increases smoothly as the temperature decreases below 20-25 K (see fig. 2). We observed no sufficient hysteresis on  $V_{aH}$  vs magnetic field curves up to temperatures as small as 1.5 K. From the experimental data we can estimate that the Curie temperature of the films with  $d_{PdFe} < 50 nm$  is about  $T_{Curie} = 15 \div 20 K$ . Note that for the film of very small thickness (5 nm)  $T_{Curie}$  is much smaller - about 7.5 K. This effect may be due to either worse structure of first atomic layers of the film or due to size effect as the film thickness of 5 nm is of the order of distance between Fe atoms.

Josephson SFS sandwiches Nb-PdFe-Nb were preparing in 5 steps. First of all we sputtered three layers (bottom Nb layer, PdFe layer and top Nb layer) in the same vacuum cycle that ensured the high transparency of SF-interfaces. On the second step we formed junction area by means of photolithography, chemical etching of

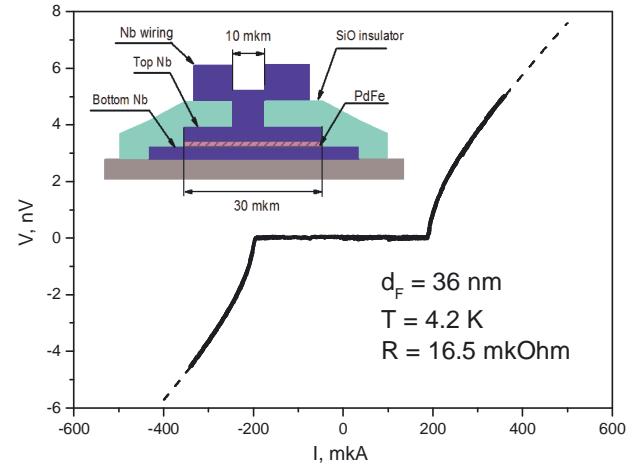


FIG. 3: Typical  $IV$  curve for josephson SFS-junctions  $Nb - Pd_{0.99}Fe_{0.01} - Nb$ . The dashed curve on the main panel shows the fit of the experimental data in order to determine the junction resistance. Inset shows a schematic cross section of the junction.

top Nb layer and ion etching of intermediate PdFe layer. The junction size was about  $30 \times 30 \text{ mkm}^2$ . The bottom Nb layer was not damaged during the chemical etching of top Nb as it was protected by chemical stable PdFe layer. On the third step we formed the geometry of the bottom Nb electrode using photolithography and chemical etching. The fourth step consisted of the sputtering of isolating SiO layer by means of thermal evaporation and lift-off photolithography. The SiO layer thickness was about 300 nm and the window size was  $10 \times 10 \text{ mkm}^2$ . On the last step we made the Nb wiring of about 400 nm thickness by means of magnetron sputtering. The geometry of top electrode was formed by lift-off photolithography. The sample was subjected to ion etching before the sputtering to ensure good superconducting contact between the top Nb electrode of the junction and the Nb wiring. The cross-section of the junction is shown on inset in fig. 3.

The IV-curves of our samples can be well described by the well known equation  $V = R\sqrt{I^2 - I_c^2}$  that allows to estimate the sample resistance as a fitting parameter. The approximation of experimental curve shown in fig. 3 gives  $R \approx 16.5 \mu\Omega$ . We assume that the junction resistance is the sum of interlayer resistance  $\rho d_F/A$  and the boundary resistance  $R_B/A$ , where  $\rho = 40 \mu\Omega \cdot cm$  is the resistivity of PdFe,  $d_F = 36 \text{ nm}$  interlayer thickness,  $A = 9 \cdot 10^{-6} \text{ cm}^2$  - junction area,  $R_B$  - the boundary resistance per unit area. So we can estimate that the  $R_B = 4.5 \cdot 10^{-12} \Omega \cdot cm^2$  and the transparency parameter [25] is equal  $\Gamma_B = R_B/AR = 0.03$ . The small value of  $\Gamma_B$  indicates the high transparency of the SF-interfaces. The  $I_c(H)$  dependance shown on inset in fig. 4 has the

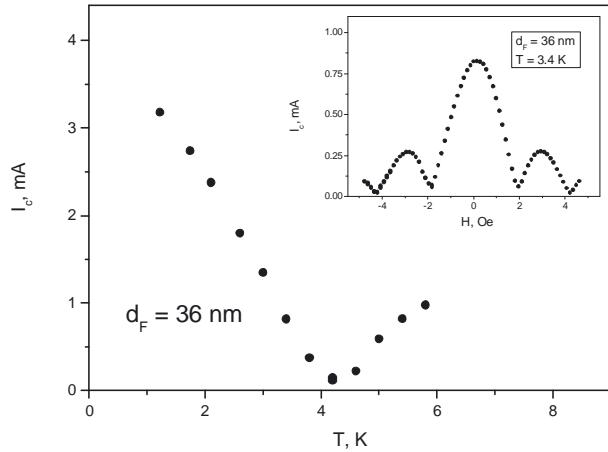


FIG. 4: The reentrant critical current vs temperature dependence of  $Nb - Pd_{0.99}Fe_{0.01} - Nb$  junction with the ferromagnetic layer thickness 36 nm. Inset shows the critical current vs temperature dependance of the junction.

form of Fraughofer pattern

$$I_c(\Phi) \sim \frac{\sin \pi \Phi / \Phi_0}{\pi \Phi / \Phi_0},$$

that points to the uniform distribution of critical current density through the area of the sample and the absence of large scale domain structure. The main result of the article is shown on fig. 4. One can see that the critical current vs temperature dependence has a reentrant behaviour at 4.2 K. As it was shown in Refs. [4] and [9] a reentrant  $I_c(T)$  curve gives an evidence of a transition into the  $\pi$ -state. However our data do not allow to specify what is the ground state of the junction (0 or  $\pi$ ) at given temperature range. To answer this question one should explore  $j_c(d_F)$  dependance in a wide range of  $d_F$  in order to estimate the period  $\lambda_{ex}$  as it was done, for example, in Ref. [9].

In conclusion, we have studied the magnetic and transport properties of  $Pd_{0.99}Fe_{0.01}$  thin films and SFS josephson junctions  $Nb - Pd_{0.99}Fe_{0.01} - Nb$ . It was found that the temperature dependance of the junction with ferromagnet layer thickness equal to 38 nm demonstrates the reentrant behaviour. According to earlier work this is the evidence of the transition of the sample into the  $\pi$ -state. Authors are grateful to V.V. Ryazanov and V.A. Oboznov for helpful discussions and N.S. Stepakov for the assistance during experiments and sample preparation. We also thank Marat Gaifullin from National Institute for Material Science (Japan) for SQUID magnetometry measurements. This work has been done under Russian Foundation for Basic Research grant 05-02-17731-a.

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